2003 Salt Marsh Vegetation Monitoring Report,

Cape Cod National Seashore

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EXECUTIVE SUMMARY

Salt marsh ecosystems are an important natural resource within Cape Cod National Seashore (CACO) that are subject to a variety of realized and potential threats. In particular, artificial tidal restrictions have had severe impacts on this habitat. As a means to evaluate the restoration of some of these hydrologically-impacted systems, a vegetation monitoring protocol was developed. Implementation of this protocol has been ongoing since 1998 in Hatches Harbor and 2002 in East Harbor, two systems where tidal exchange has been restored after long periods of impoundment. In 2003, field crews expanded the data gathering effort to include new sites in unrestricted marshes, while continuing to monitor the restoration sites. As a component of this additional monitoring, a suite of new biotic and abiotic variables were characterized in order to evaluate their potential inclusion into the existing protocol.

Vegetation monitoring in CACOs unrestricted salt marsh habitat revealed that although different sites harbored similar kinds of salt marsh plants, their relative abundances varied substantially, particularly with respect to macroalgae (seaweeds). Another interesting find was that cordgrass (*Spartina alterniflora*) exhibited a level of productivity, as suggested by plant heights and leaf nutrient content, similar to or surpassing that which has been reported from numerous marshes along the Atlantic and Gulf coasts. The physico-chemical attributes of CACO marshes such as hydroperiod and porewater sulfide concentrations were also quite disparate and, in addition to developmental stage (age), undoubtedly contribute to variability in structure and function.

In East Harbor, plant community composition has exhibited some transformation in response to hydrologic restoration, mostly in the area immediately upstream from the point of seawater entry. While much of the emergent salt-intolerant vegetation that became established during the period of tidal restriction has been suppressed or disappeared altogether, no salt marsh species have yet emerged from the seed bank. The aerial extent of *Phragmites* remains unchanged; however, minor reductions in plant heights, photosynthesis, and flowering have occurred, which coincide with elevated porewater salinities and sulfides. The rate of *Phragmites* decline may initially be slowed by the ameliorating effects of heavy precipitation and temporarily increased porewater nutrient availability.

In Hatches Harbor, a number of changes occurred during 2002-2003. Although *Phragmites* appears to have made a slight recovery in places, probably due to copious rainfall in June and July of 2003, other indicators such as flowering and leaf tissue nutrient concentration suggest a continuing decline in vigor. Moreover, native halophytes are rapidly spreading throughout the formerly restricted portion of the marsh - a trend that should be statistically apparent following a complete vegetation survey scheduled for 2004.

INTRODUCTION

Overview of salt marsh vegetation monitoring

Salt marsh ecosystems are an important natural resource within Cape Cod National Seashore (CACO). In addition to their aesthetic value, their role in supporting a wide variety of flora and fauna has been well documented (Nixon and Oviatt 1973, Roman et al. 2001). Salt marshes also reduce coastal erosion, attenuate nutrient inputs to the marine environment, and protect shorelines by dissipating energy from storm surges (Bertness 1999).

While many salt marsh areas within CACO are relatively pristine, others have been severely degraded by human-related activities. Restrictions to tidal flow, for example, have had major impacts on this habitat, which has led to several restoration initiatives. In 1997, a series of large culverts were built into the dike that had severed much of Hatches Harbor from seawater influence for > 40 years. In 2003, efforts to restore East Harbor, a salt marsh lagoon impounded for ~ 150 years, were undertaken by permanently opening clapper valves in a culvert that connects the system to Cape Cod Bay. Vegetation monitoring was initiated at both these sites prior to restoration and this work led to the development of a long-term protocol for salt marsh vegetation monitoring (Roman et al. 2001). In a broader context, eutrophication, sea-level rise, acid deposition, and recreational use are additional threats to salt marsh habitat. The protocol allows scientists and managers to evaluate the progress of restoration as well as changes in unrestricted salt marsh habitat throughout CACO. Some of the primary questions that the protocol addresses are:

- What is the response of salt marsh vegetation to hydrologic restoration?
- How do salt marsh structure, function, and landscape pattern of salt marsh vegetation vary spatially and temporally?
- What physical, chemical, and biological factors contribute to observed variation?
- Are certain features and changes in characteristics the result of human activities or natural processes?

In 2003, field crews focused on the implementing the current protocol for salt marsh vegetation monitoring at both preexisting (Hatches Harbor, East Harbor) and new sites, the latter being established in four areas of hydrologically-unaltered salt marsh habitat. Vegetation communities and a number of physico-chemical parameters were characterized in detail. In addition, data was collected for several new parameters that will be evaluated for possible inclusion into the protocol (see section on "Data Collection").

METHODS

Baseline characterization of CACO's unrestricted salt marsh habitat

The basic techniques for monitoring salt marsh ecosystems at CACO have already been developed and are summarized in Roman et al. (2001). To date, monitoring efforts have largely focused on tracking the progress of tidal restoration. Consequently, we began collecting baseline data on vegetation and physico-chemical characteristics of unrestricted marshes in 2003 to provide a foundation for the long-term monitoring of salt marsh habitat CACO-wide. Moreover, information from unrestricted sites allows scientists and managers to evaluate restoration projects based on specific quantitative targets for physical, chemical, and biological attributes.

Establishment of new sites

Within the boundaries of CACO, there are four main areas of unrestricted, salt marsh habitat (two on the Atlantic and two on the Cape Cod Bay side). The West End marsh is adjacent to Provincetown and is enclosed along its eastern margin by a permeable stone dike originally installed to prevent sediment transport into Provincetown Harbor. The western boundary is a barrier beach that ends at Long Point. Middle Meadow, located on Great Island in Wellfleet, is wedged between two upland areas to the north and south. Nauset marsh in Eastham is a part island - part back barrier marsh that lies between Town Cove and a spit (Coast Guard Beach). The Pleasant Bay site is located in the northeastern reaches of Pleasant Bay in Orleans and extends westward from the barrier beach (Nauset Beach) (Figure 1). Hatches Harbor lies at the western edge of Seashore (Provincetown) and is bisected by an earthen dike, into which culverts have been installed for the purpose of tidal restoration. As mentioned previously, monitoring has been conducted at permanent plots since 1997 in both the unrestricted and restoring (formerly-restricted) sides of the marsh.

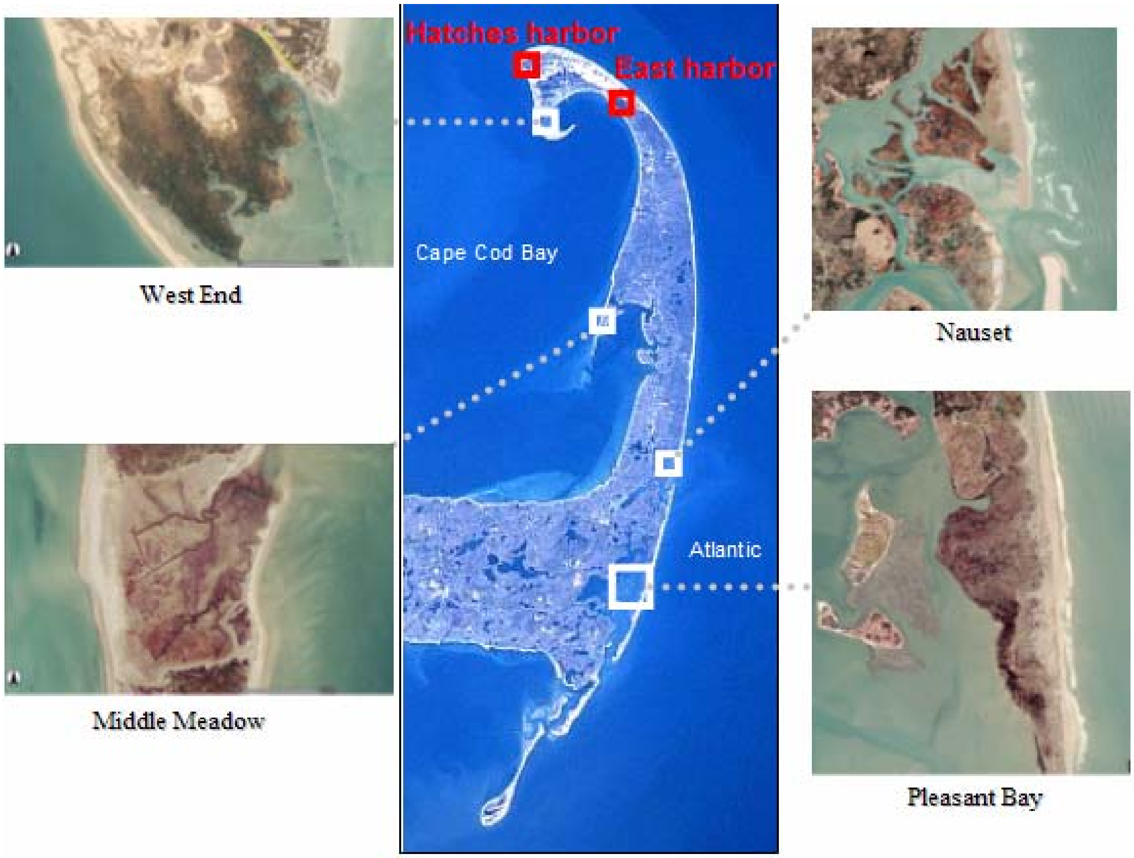


Figure 1. Salt marsh monitoring site locations within CACO.

Transect and plot locations were laid out according to the general methods of Roman et al. (2001). As a means to circumvent various on-the-ground difficulties such as stretching field tapes over long distances through dense vegetation and across wide tidal creeks, orienting transects with a compass, etc. GIS software was used to locate sampling points. The procedure is described below:

1. Aerial photographs of each marsh area were imported into Arcview™ ver. 3.2. Using the drawing toolbar, straight lines were created at roughly right angles to elevation gradients or, when no gradients were obvious, along the major axis of the marsh, which was based on general marsh configuration. In all cases, the axes essentially bisected each area of salt marsh habitat. Three points were then randomly located (using a point randomization Arcview™ extension) along the main axis. Where a minimum of three transects did not seem to adequately capture the overall character of a marsh (based on marsh size, vegetation gradients, and geomorphic features), we added transects until all the major features were represented.

2. Transects, delineated as additional straight lines, were drawn perpendicular to the main axis intersecting with each randomized point. Transects were made to extend from one edge of the marsh to the other, with edges being defined as either upland or open water.

3. A point within 20m from the end of each transect was randomly located. From this point, all other points (= plot locations) were plotted by a standard distance, which was 30, 60, or 100 m depending on marsh size (Figure 2).

Based on several years of data from the unrestricted portion of Hatches Harbor, Roman et al. (2001) suggest that 20 plots re sufficient to characterize unrestricted Cape Cod salt marsh communities. The method described above placed between 20 and 40 sites within each site (see Appendix I). Plot coordinates were uploaded into a Garmin™ GPS receiver and located in the field. To mark each site, a length of 1.25-inch PVC pipe was hammered into the ground to a depth of ~ 3 ft.

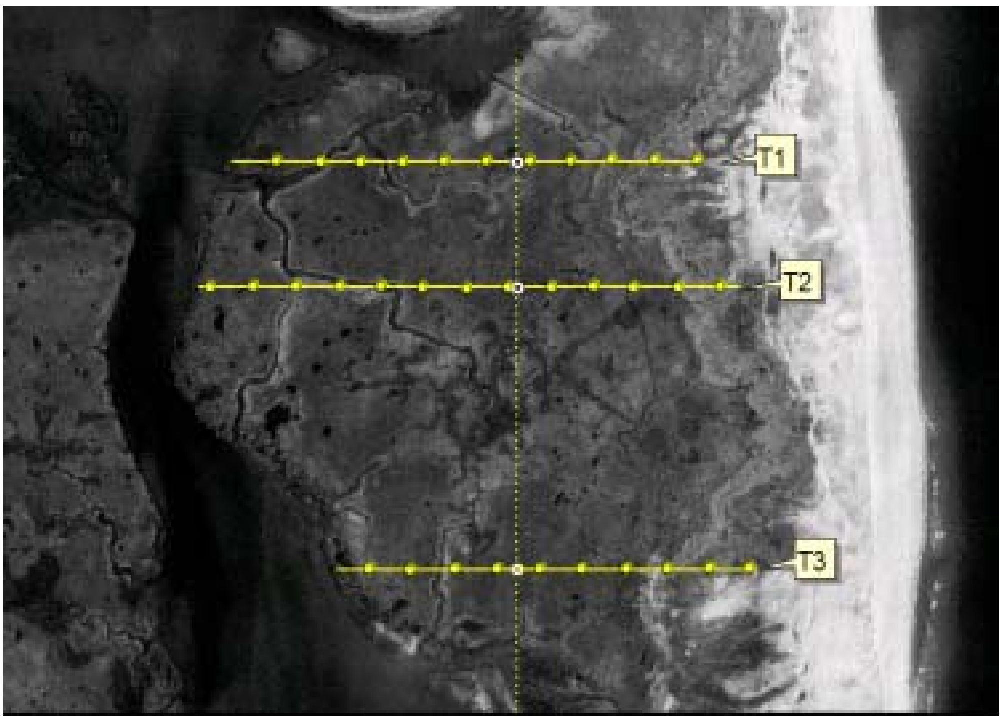


Figure 2. Resulting configuration of transects and plots using GIS software (Pleasant Bay marsh site, Orleans).

Data Collection

To characterize the biotic and abiotic environment, data were collected for the following parameters:

- Percent area cover of vegetation by species (Roman et al. 2001)

- Porewater quality (salinity, pH, alkalinity, H_2S, NH_4, PO_4) (spring tides during June & August) (Portnoy and Giblin 1997)

- Sediment solid phase properties (particle size, bulk density, organic matter, KCL extractable NH_4, total iron, total sulfur, total phosphorus, TC, TN, inorganic phosphorus, organic phosphorus) (Portnoy and Giblin 1997); total reactive Fe (amorphous Fe(III) oxides and acid volatile Fe sulfides, Kostka & Luther 1994)

- Water table heights at low tide - Hydroperiod, particularly as it relates to sea-level rise, greatly influences marsh structure and function (Donelly and Bertness 2001). Water depths were measured once during a neap low tide period. Because it is impossible to do this simultaneously in all marshes, individual marshes were monitored on specific days during October, November, and December when the high and low tides were expected to reach the same or very similar elevations (based on local tide charts for the area). In this way, although the data were collected on different days, the tidal conditions for each site were very close to what they would be if measured on a single day. This will allow for a more powerful spatial analysis of hydrologic variability.

These additional parameters also were sampled in an attempt to evaluate other biogeochemical indicators of salt marsh health and to provide a more comprehensive understanding of these systems:

- *Spartina alterniflora* heights - Heights of individual *S. alterniflora* are frequently used as an indicator of physiological state or "vigor" (Lissner and Schierup 1996, Chambers 1997, Neckles et al. 2002). Where *S. alterniflora* was present, the heights of the 5 tallest plants, which is representative of aboveground biomass (Thursby et al. 2002), were measured within each m^2 plot.

- *Spartina alterniflora* flowering - Because the production of an inflorescence in *S. alterniflora* is affected by stress, the presence/absence of flowering stems was noted for each plot (Neckles et al. 2002).

- Plant tissue nutrients - Leaf nitrogen (N) and carbon (C: N) are useful indicators of plant vigor and estuarine trophic status (Bradley and Morris 1992, Farnsworth and Meyerson 2003). In August, three to four live leaf segments (~20 cm from tip of the leaf) were collected from 3 separate *S. alterniflora* plants (adjacent to each plot) and composited. Macroalgae, if present, were collected as well. The samples were immediately dried, ground, and analyzed for total carbon (TC) and nitrogen (TN) content (Lee 2003).

- Infiltration rates - to assess their capacity for gravimetric drainage, soils adjacent to each plot were cored to a depth of 10 cm using 2-inch diameter butyrate tubes. The cores were capped and transported back to the laboratory. Each core was mounted vertically on a rack and the bottom cap replaced with a section of 2-inch (inside diameter) PVC pipe across which a piece of 1 mm nylon mesh was fastened. The tube served as a filter that allowed water to pass through but retained the sediment. Water was added to each core to uniformly saturate the samples. While temporarily capping the bottom with a piece of styrofoam in one hand, additional water was then added to a level 20 cm above the sediment surface, after which the water was allowed to drain freely. Using a dry-erase marker, the water level was marked directly on the tubes at different times before it reached the sediment surface. The rate of change was then calculated as mean volume lost per second.

- Peat depths - The depth of peat in a marsh is important in terms of nutrient pools, drainage rates, and physical stability. Peat depth variation is a reflection of marsh hydrology, sediment dynamics (supply and erosion), and marsh age. To determine average peat depth at a particular location, a 2m-long aluminum pipe with a plastic end cap was used as a probe to detect the boundary between peat and inorganic sediment layers. In three separate locations adjacent to each plot, the probe was pushed into the marsh surface until it reached the sand barrier, at which point there is sudden resistance to further penetration. In most cases, this peat-sand interface can also be confirmed audibly as passage through sand makes a loud grinding sound.

- Presence or absence of fiddler crabs and their burrows - Fiddler crabs (*Uca* spp.) can alter porewater-sediment chemistry and, consequently, plant vigor (Bertness 1985, Michaels and Zieman 2003).

- Digital photographic inventory - Images of each vegetation plot were acquired with a digital camera. This kind of digital inventory not only helps to convey community changes over time, but also serves as a useful tool for data referencing and quality control. Details on acquiring mages are given in section IV below.

East Harbor

East Harbor was originally a salt marsh lagoon with a ~1,000 ft opening to Cape Cod Bay. In the mid-1800s, the mouth of this lagoon was closed off in an attempt to prevent shoaling in Provincetown Harbor. Shortly thereafter, a railroad was built and, except for a 4-ft diameter culvert that allowed one-way drainage out to sea, the waterbody was completely impounded. The bordering marsh areas subsequently were invaded by freshwater wetland taxa with *Typha angustifolia* one of the dominant plant. *Phragmites australis*, a brackish water species, also invaded the system, primarily in the Moon Meadow area just north of the culvert opening. In December 2001, the clapper valves in the culvert connecting the Harbor with Cape Cod Bay were permanently opened in the interest of hydrologic restoration. Prior to this date, a series of 1m^2 sampling plots along 4 transects were established to monitor changes in physico-chemical parameters and the vegetation community (see Appendix I). Monitoring activities begun in 2002 were continued throughout 2003. The following is a brief description of sampling variables:

<u>Vegetation</u>

Plant densities were determined by manual counting and species cover by visual estimate by cover class. The latter method was used in lieu of the point intercept technique due to the difficultly of positioning point-counting rods in extremely dense, tall vegetation. In addition, all stems of *Typha angustifolia* and *Phragmites australis* (where present) were measured from base to highest portion of stem (leaf tip or top of inflorescence). When densities were extremely high (e.g., > 50) the measurements were restricted to the bottom left (or "southwest") corner ($0.25m^2$) of the m^2 plot. Photosynthetic gas exchange of *Phragmites* was measured in a subset of plots and in stands around the lake shoreline on July 18, 2003 using an infrared gas analyzer. Finally, three or four live leaf segments (~20 cm from tip of the leaf) were collected in August from 3 separate *Phragmites* plants adjacent to the m^2 plot and composited. The samples were immediately dried, ground, and analyzed for total carbon (TC) and nitrogen (TN) content.

<u>Porewater quality</u>

Triplicate porewater samples (10 cm depth) were collected from each plot during neap tide cycles in June and August. Three 10-ml samples were drawn by a syringe fitted with a stainless steel probe. A 500 uL subsample was drawn directly from each replicate with a 20-gauge needle on a glass syringe; total dissolved sulfides in this aliquot were immediately fixed by ejecting the sample through the needle into a 20-ml septum vial containing 6 ml of zinc acetate (see appended sulfide method). All three of the larger samples were then transferred via a rubber connector to a common syringe, resulting in a composite 30 ml sample. The syringes were capped and transported in coolers with freezer packs back to the laboratory. Salinity, pH, and alkalinity measurements were made immediately upon return. Remaining sample was filtered (0.45 µm Millipore), acidified to pH < 2 with trace metal grade HCl and stored at 4ºC for subsequent analyses of NH_4, PO_4, and Fe.

Hatches Harbor - Restoring Side

Hatches Harbor has been undergoing hydrologic restoration since 1997, accompanied by intensive monitoring (Portnoy et al. 2004). During this time, plant communities upstream of the dike have exhibited rapid changes. Prior to the construction of culverts that now allows tidal exchange, the upstream portion of the marsh had been invaded by the exotic haplotype of *Phragmites* australis, which effectively displaced a large portion of the native community. As such, tracking the response of *Phragmites* to the reintroduction of seawater is a major component of evaluating the progress of restoration.

<u>Vegetation</u>

Phragmites stems heights and densities were recorded in a subset of plots (0-240m) along transects 1 and 2 at the end of the 2003 growing season (mid-October). The presence or absence of an inflorescence on each stem was also noted at this time. Earlier in the growing season (July), *Phragmites* leaf samples were collected from plants adjacent to these plots and analyzed for carbon and nitrogen content by standard methods (Lee

2003). Tissue nitrogen (N) and carbon C:N can be useful indicators of plant vigor and wetland trophic status (Bradley and Morris 1992, Stribling and Cornwell 2001, Farnsworth and Meyerson 2003). Statistical comparisons were conducted using specific T-tests for groups having equal or unequal variances.

Porewater

Porewater samples were obtained from a subset of plots along transects 1, 2, and 7 by the methods described above.

Resolution of General Logistical Issues

Plot marker/water well design

It is important to position plots in the same location for repeated sampling. When using a single marker to delineate one corner of a plot, quadrats can easily be offset from the original placements, which can lead to sampling error (Figure 3). To avoid this scenario, two markers were used to indicate the location of two opposite corners, the disadvantage being that twice as much marker material (e.g., PVC pipe) is needed.

Figure 3. Example of how misalignment of a quadrat can produce significant sampling error. Note that the *Spartina alterniflora* in the upper portion of the original sampling area would not be recorded in a subsequent plot offset by 20º.

A new plot marker design allowed us to reduce the amount of PVC required to define the sampling area while maintaining the spatial integrity of the plot (Figure 4). A hole was drilled completely through the top of each PVC pole. To set up the plot, a 1.41 m plastic dowel was inserted through both holes (and thereby held firmly at that particular angle). The end of this dowel indicated the location for the opposite corner of a $1m^2$ quadrat and the sides of the square could be set up based on this reference point.

Figure 4. Image showing how a single plot marker can be used to orient a $1m^2$ quadrat.

The PVC plot markers also functioned as water wells, which were fashioned according to substrate type. Sandy or mucky substrates required slot wells with diameters < 0.5 mm (to prevent sediment intrusion). In consolidated peat, we used wells with larger holes drilled into the sides to facilitate flow and, therefore, more rapid water-level compensation (as described in Roman et al. 2001). Wells were cut to 3-4 ft. in length (with approximately 6 inches out) so that they could reach the water table in well drained soils and to make then difficult to remove. A rubber mallet was used to hammer in the PVC pipe to avoid shattering and/or disfiguring the end of the pipe.

<u>Plot labeling</u>

Establishing permanent labels on plot markers is an integral part of data quality assurance. Unfortunately, permanent ink fades quickly with exposure to sun, wind and rain. Even aluminum tags degrade rapidly in the marine environment. Our solution was to write plot codes in permanent ink on the inside of PVC caps placed on the ends of each marker (friction fit) (Figure 5). Protection from the elements has allowed the labels to persist; to date (~12 months of exposure) there has been no detectable fading.

Figure 5. Image of plot ID label on inside of PVC socket cap, which fits over the end of the marker/well.

Photographic inventory

The acquisition of digital images of each plot (Figure 6) can contribute significantly to data quality control. In addition, these images provide a good way to convey information to a variety of audiences. Images should be taken from as overhead a position as possible in order to minimize aerial distortion and plot boundaries should be visible. As a rule, the photographer should stand in a position to minimize shadows and photo orientation and date should be noted in the metadata.

Figure 6. Example of a suitable picture for the digital image library of monitoring plots.

RESULTS AND DISCUSSION

Hatches (unrestricted), Middle Meadow, Nauset Island, Nauset mainland, Pleasant Bay, and West End marshes

Vegetation

A total of twenty-three species of vascular plants and four species of macroalgae were recorded within the plots (Table 1). Cyanobacterial mats were present across unvegetated flats in one marsh (Nauset mainland). Average numbers of species per plot ranged between 2.7 in Nauset Island and 1.6 in Pleasant Bay. Macroalgae abundance and composition varied markedly, with the West End and Hatches marshes having abundant *Fucus vesiculosis* and *Ascophyllum nodosum*. No macroalgae was observed in the Middle Meadow or Pleasant Bay plots. The total number of species observed in each marsh (irrespective of plot data) showed a higher degree of variation, ranging between 8 species in West End to 15 species in Middle Meadow and Pleasant Bay. We suspect this is related to differences in elevation ranges, which will be determined in 2004.

Table 1. Vascular plants and macroalgae recorded in salt marsh monitoring plots.

Ammophila breviligulata	(beachgrass)
Ascophyllum nodosum	(knotted wrack)
Atriplex prostrata	(triangle orache)
Baccharis halimifolia	(groundsel tree)
Cakile edentula	(sea rocket)
Chaetomorpha linum	(green algae)
Cyanobacteria spp.	(blue-green algae)
Distichlis spicata	(spike grass)
Elymus repens	(quack grass)
Festuca rubrum	(red fescue)
Fucus vesiculosis	(bladder wrack)
Juncus gerardii	(black grass)
Limonium carolinianum	(sea lavendar)
Myrica pensylvanica	(northern bayberry)
Plantago sp.	(plantain)
Puccinellia maritima	(alkali grass)
Salicornia biglovii	(dwarf saltwort)
Salicornia maritima	(slender glasswort)
Salicornia virginica	(Virginia glasswort)
Solidago sempervirens	(seaside goldenrod)
Spartina alterniflora	(smooth cordgrass)
Spartina patens	(saltmeadow cordgrass)
Spergularia marina	(salt sandspurry)
Suaeda linearis	(annual seepweed)
Suaeda maritima	(herbaceous seepweed)
Toxicodendron radicans	(poison ivy)

Although total numbers and types of species were very similar among marshes, community composition, as indicated by Principal Components Analysis of species mean cover values (all plots pooled), showed large differences (Figure 7). Geography, which is also indicative of marsh age, emerged as a distinct feature of the observed variability in that the Eastham (Nauset Island, Nauset mainland) and Provincetown (Hatches Harbor, West End) marshes were grouped closely together, while the Wellfleet (Middle Meadow) and Orleans (Pleasant Bay) marshes were separated from the rest and from each other. Species diversity/evenness indices also reflected these differences (Table 2).

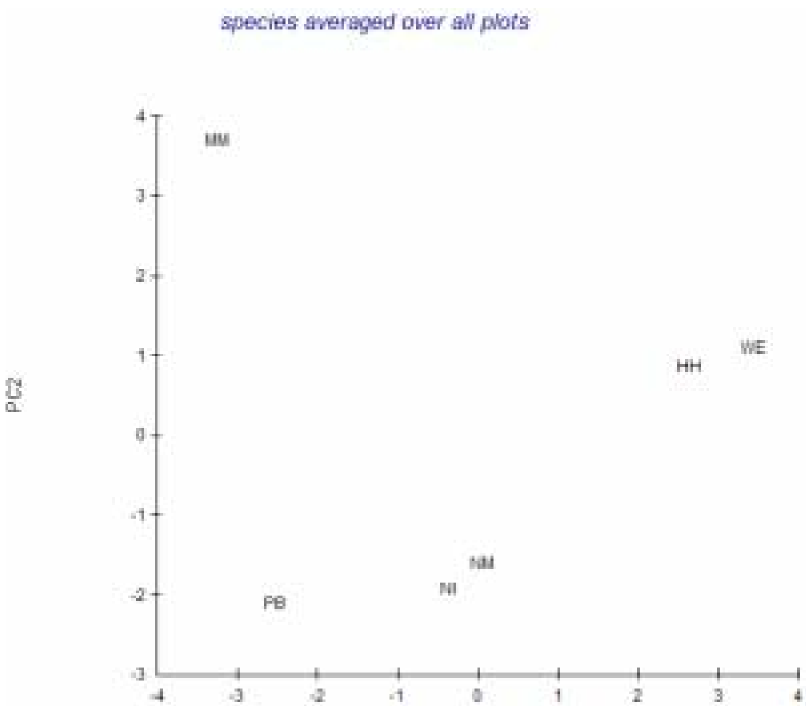


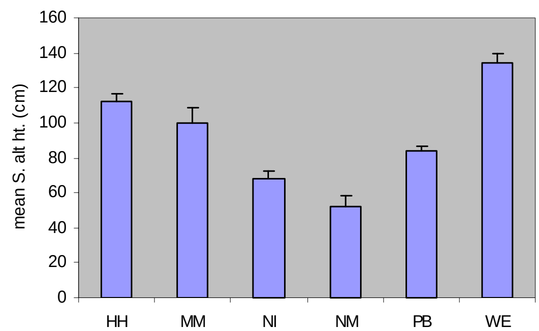
Figure 7. Principal components analysis of mean percent cover by species.

Table 2. Shannon-Weiner diversity (D) and Pielou's Evenness (E) indices for mean species percent cover values (all plots pooled).

Marsh	D	E
Hatches Harbor	1.894	0.7897
Nauset Island	1.253	0.5442
Nauset Mainland	1.351	0.6148
Middle Meadow	1.591	0.6404
Pleasant Bay	1.288	0.3426
West End	1.748	0.7035

Grand mean height values (i.e., means all plots pooled) of the tallest five *S. alterniflora* plants were lowest in Nauset Island and Nauset Mainland marshes (Figure 8a). In Hatches Harbor and West End, however, plants were very tall with maximum heights exceeding those that have been reported in numerous other studies (Table 3). Ranges of individual plot means followed a similar pattern. Plants in Middle Meadow and West

End marshes exhibited the largest variability in heights while those in the Nauset marshes were more uniform (Figure 8b).



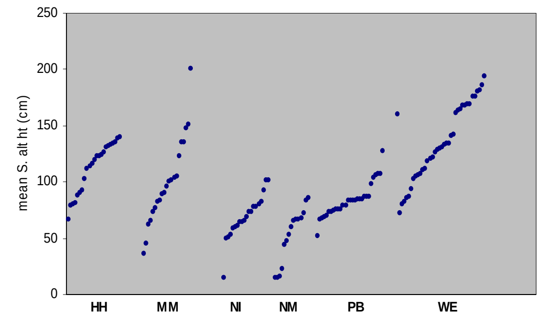


Figure 8. Mean *S. alterniflora* plant heights for a) all plots pooled and b) individual plots (based on 5 tallest plants recorded in each plot).

Table 3. Reported end of growing season heights of *S. alterniflora* from Atlantic and Gulf Coast States ("fertilized" indicates plants subjected to artificial nutrient enrichment).

State	Mean heights (cm)	Total range (cm)	Reference
LA	78-93		Lindau and DeLaune (1997)
LA	42		Michot et al. 2001
CT		< 200	Chambers (1997)
RI	50-142		Nixon and Oviatt (1973)
MA	30 (control)		Howes et al. (1986)
	102 (fertilized)		Howes et al. (1986)
VA		41-56	Tyler and Zieman (1999)
SC		< 200	Morris and Haskin (1990)
VA	51-115 (controls)		Osgood and Zieman (1993)
	61-154 (fertilized)		Osgood and Zieman (1993)
VA	70 (fertilized)	30-150	Osgood and Zieman (1998)
SC	70.5 (fertilized)		Bagwell and Lovell (2000)
	28.7 (control)		Bagwell and Lovell (2000)
RI		16-180	Thursby et al. (2003)
MA	120 (tallest 10)		Teal and Howes (1996)
MA		31-166	Plum Island database
MA		122-183	Redfield (1972)
MA, CT	100		Farnsworth and Meyerson (2003)
LA	64 (fertilized)		Buresh et al. (1980)
	51 (control)		Buresh et al. (1980)
RI	41-136		Wigand et al. 2003
MA	56-137 (tallest 5)	7-240	this study

Tissue N content ranged from an average of 1.3% in Pleasant Bay to 1.9 in the West End marsh. Since N assimilation is inhibited by poor drainage and high sulfide concentrations, leaf N content may reflect differences in plant vigor. The leaf N and C:N of live *S. alterniflora* leaves in some of the marshes were also quite high compared to those reported in the literature (Table 4). Perhaps more importantly, the leaf tissue nutrient data indicate that *S. alterniflora* appears not to be limited by nitrogen based on estimated minimum N concentrations required to support growth in this species (Bradley and Morris 1992). This would be in contrast to the many salt marshes along the Atlantic and Gulf coasts, which are N-limited (Day et al. 1989). High N content may also be the result of atmospheric deposition which is substantially higher in the northeastern states (NADP) or it may simply be related to the large tidal ranges on Cape Cod (Streever et al. 1976, Day et al. 1989). The contribution of land-derived nitrogen to CACO salt marshes is unknown, although it is interesting to note that some of the highest N concentrations were found in plants from the West End marsh - the only site immediately adjacent to a major urban center (Provincetown). The abundance of macroalgae in this marsh, which has been shown to enhance the growth of *S. alterniflora* elsewhere (Gerard 1999), may also be part of the explanation. Additional sampling from locations receiving widely differing inputs of land-based anthropogenic N (i.e., southern tip of Monomoy Island vs. Muddy River) and isotopic analysis (i.e., $^{15}N/^{14}N$) may help, in conjunction with the estuarine nutrient enrichment protocol, clarify these issues (Wigand et al. 2003).

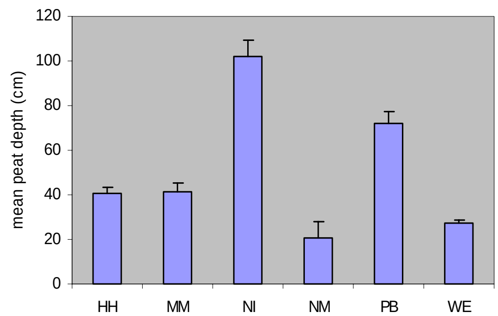
Table 4. Reported leaf nitrogen content of *Spartina alterniflora* ("fertilized" indicates plants subjected to artificial nutrient enrichment).

State	Date	N (%)	Reference
SC	Aug	<1 (control)	Morris (1982)
		>2 (fertilized)	Morris (1982)
LA	NA	2.1 (fertilized)	Breitenbeck (not dated)
		1.4-1.8 (control)	Breitenbeck (not dated)
VA	Jun-Sep	1.2-2.1	Tyler and Zieman (1999)
SC	n/a	0.8-1.4	Bradley and Morris (1992)
MD	Aug	0.7-1.2 (shoots)	Stribling and Cornwell 2001
GA		1.3-1.6	McIntire and Dunstan (1976)
NC, GA		<1.1	Broome et al. (1975)
MA, CT	Aug	1.6	Farnsworth and Meyerson (2003)
GA	Jul-Aug	1.4-1.5	Haines (1979)
LA	Jun	0.8-1.0	Brannon (1973)
LA	Jun	<1.1	Buresh (1980)
DE	Jun-Sep	0.9-1.0	Roman and Daiber (1984)
GA	Aug	<1.0 (control)	Chalmers (1979)
		<1.3 (fertilized)	Chalmers (1979)
VA		0.7-0.9	Gallagher (1975)
VA		0.7-0.9	Patrick and DeLaune (1976)
VA		1.0-1.5	Mendelssohn (1973)
CA	Sep	0.9	Daehler and Strong 1997
WA	Sep	1.3	Daehler and Strong 1997
MD	Sep	1.0	Daehler and Strong 1997
FL	Aug	1.2 (control)	Stiling et al. (1982)
		1.6 (fertilized)	Stiling et al. (1982)
FL	Jun	<1.5 (control)	Bowdish and Stiling (1998)
		<2.1 (fertilized)	Bowdish and Stiling (1998)
MA	Aug	1.3-1.9	this study

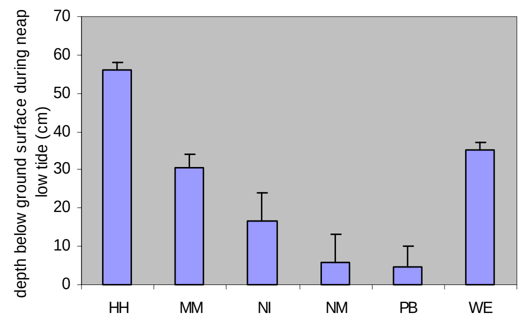
Physico-chemical environment

Mean peat depths differed significantly among marshes, ranging between 20.7 (Nauset mainland) and 102 cm (Nauset Island) (Figure 9a). With the exception of Nauset mainland, which experienced overwash events in 1987 and 1991, the Atlantic side marshes (Pleasant Bay and Nauset) had much thicker peat than Cape Cod Bay marshes*

* Older Cape Cod Bay marshes have deeper peat than the Atlantic marshes; it's just that they are diked, e.g. upper Pamet River, Herring River.



(a)



(b)

Figure 9. Mean a) peat depth and b) water depth at low tide by marsh.

Depth to water during the neap low tide cycle showed major variation, with nearly a tenfold difference between Hatches Harbor and Nauset Mainland marshes (Figure 5b). As such, salt marsh vegetation in the Nauset and Pleasant Bay must cope with extreme flooding stress (i.e., anaerobic and anoxic conditions) compared with the other systems. Porewater and sediment exhibited significant variability among marshes. The most notable differences were in particle size and sulfide, NH_4, and PO_4 concentrations. For example, porewater sulfide concentrations in Pleasant Bay were more than threefold those found in the other marshes. Histograms depicting mean values for these and other parameters are included in Appendix II.

Symptoms of marsh deterioration in Pleasant Bay?

An area of salt marsh adjacent to transect 1 in Pleasant Bay appears to be showing some symptoms of deterioration. Specifically, we observed what appears to be loss in area coverage of *S. alterniflora* and the development of extreme topographic variation. With respect to the latter, the ground surface has become pockmarked with open depressions surrounding isolated hummocks of *S. alterniflora* - a feature that is unlike any of the other marshes within CACO. Coincidentally, this marsh also has the highest concentrations of insects, including the marsh grasshopper. This may be a sign that *Spartina alterniflora* is under physiological stress and that insects are exploiting weaknesses in its chemical defenses. The source of stress may be increased flooding given that a break in the barrier spit occurred in 1987, which had the effect of immediately increasing the tidal amplitude of Pleasant Bay. As such, special attention should be paid to document any further signs of degradation in this system.

East Harbor

<u>Vegetation change (2002-2003)</u>

With the opening of the culvert and increased salinity, virtually all species except *Phragmites* disappeared from transects EH3 and EH4. There was less change in vegetation along transects EH1 and EH2 (Figure 10) where *Typha angustifolia* and associated freshwater species continued to thrive in a low-salinity environment (Figure). *T. angustifolia* is reportedly intolerant of salinities greater than ~15 ppt (Whigham et al. 1989), which explains its disappearance from the higher salinity (> 25 ppt) Moon Meadow area (transects EH3 and 4). Salt-intolerant species such as *Thelypteris palustris* (marsh fern), *Onoclea sensibilis* (sensitive fern), *Toxicodendron radican* (poison ivy), and *Impatiens capensis* (jewel weed) survived in EH1 and EH2 plots but not in Moon Meadow.

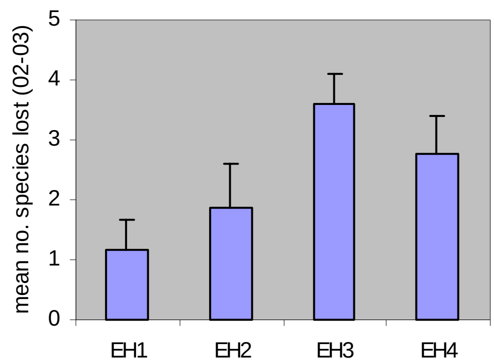


Figure 10. Mean number of species absent from transects (all plots pooled) after 1 year of tidal restoration (2002-2003).

<u>Phragmites</u>

In total (i.e., all plots pooled), stem heights at the end of the growing season were significantly lower in 2003 than in 2002 (Figure 11). When broken down by individual plots, it becomes evident that reductions occurred in some plots but not others. By and large, the greatest reductions occurred in plots closer to the main tidal creek (Figure 12).

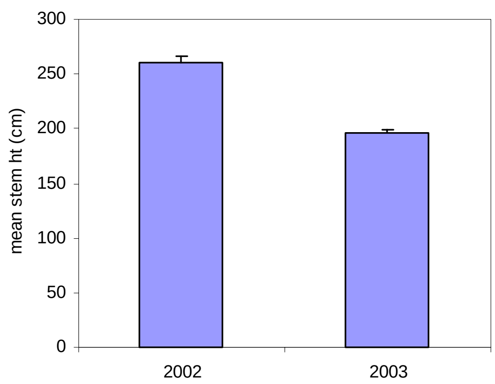


Figure 11. Mean end of growing season stem heights (all plots pooled) of *Phragmites australis* in Moon Meadow.

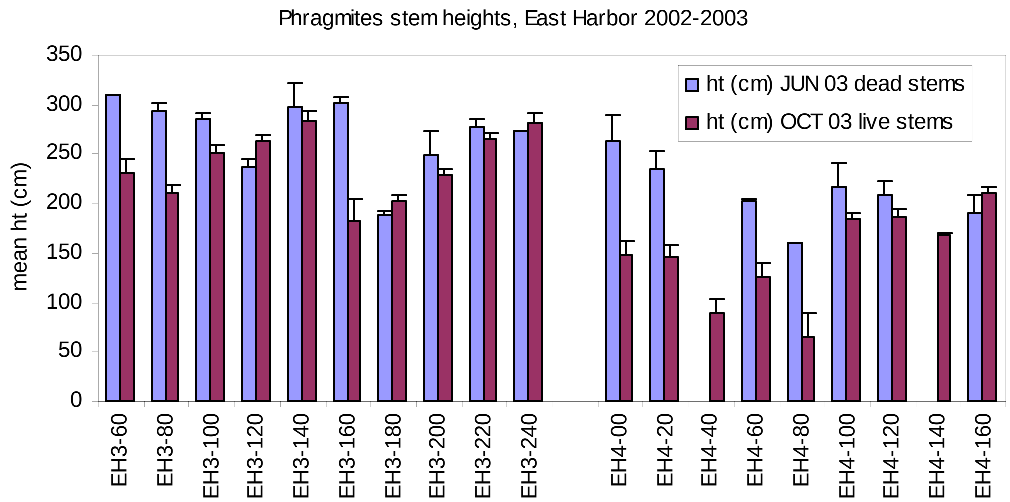


Figure 12. Mean stem heights of *P. australis* by plot in 2002 and 2003 (end of 2002 growing season mean heights determined from standing dead stems present in June 2003).

In contrast to stem height trends, *Phragmites* stems were much denser in both June and October of 2003 compared to June 2002 (Figure 13). The reason for this is unclear. However, we suspect that record amounts of precipitation in May and June lowered surface salinities to a level that allowed for vigorous growth during this period, which sharply contrasts early growing season conditions in 2002 when a prolonged drought occurred. Around mid-summer the plants began to exhibit stress and some die off occurred, which brought stem densities back down. Unfortunately, stem heights and densities were not measured in the fall of 2002. This is because we assumed that a measure of standing dead stems with intact inflorescences adequately represented the previous year's growth. In observing *Phragmites* populations throughout the winter, however, it has become clear that high winds and storms can break many of the stems produced the previous summer. As a result, measurements taken only on standing dead stems with a inflorescences are not reliable for calculating biomass and direct annual comparisons cannot be made for this time of year. As a general observation, *Phragmites* was not reduced after 1 year of tidal restoration. Instead, the population changed form, becoming shorter, but denser.

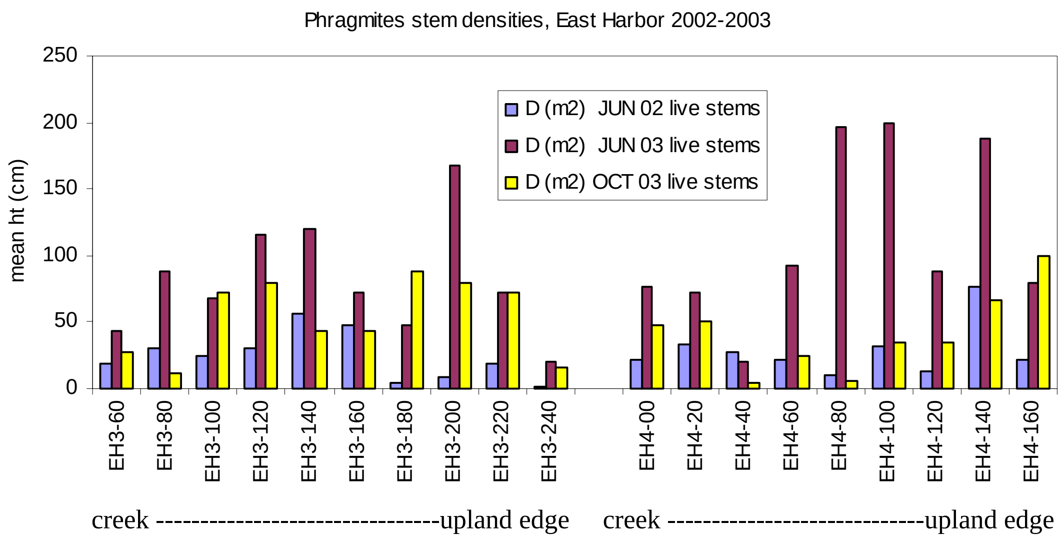


Figure 13. Stem densities of live *Phragmites* along transects EH3 and 4 in 2002 and 2003.

Despite an early surge in growth, mid-summer (July 03) photosynthetic gas exchange was suppressed in *Phragmites* growing within Moon Meadow compared to those in other areas of fringing marsh (Figure 14). Porewater salinities in June and August ranged between 25-32 ppt in the former (yellow circles) and 5-15 ppt in the latter (blue circles).

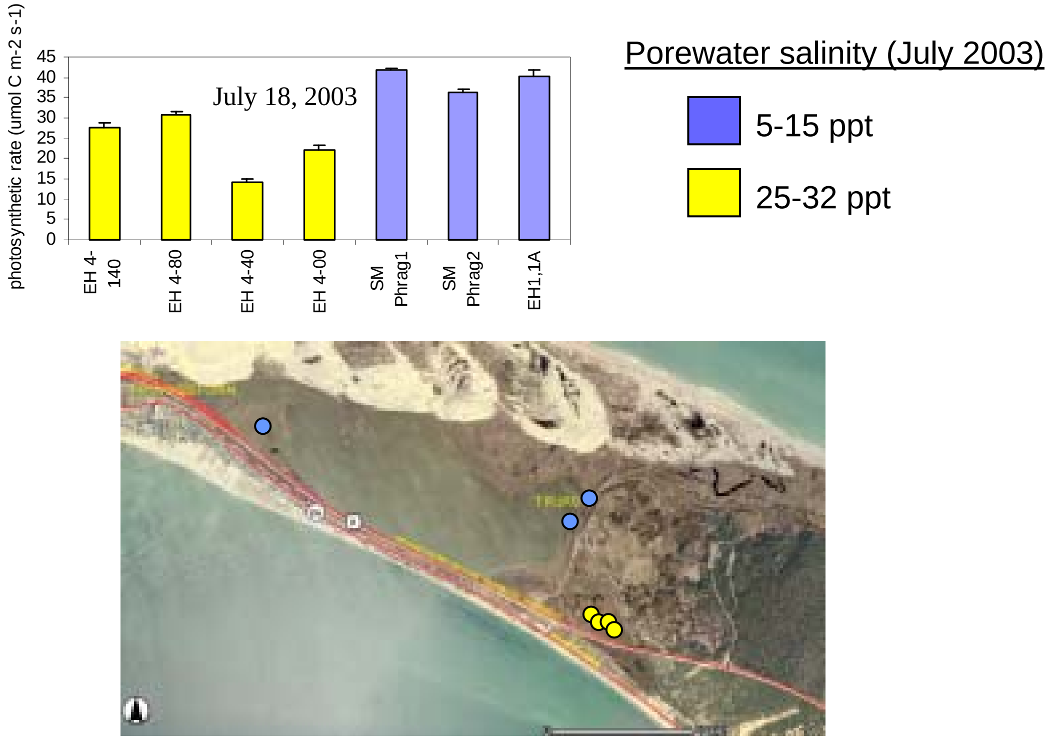


Figure 14. Mid-summer photosynthetic rates of *P. australis* at various locations around East Harbor.

Phragmites leaf tissue N exhibited a significant decrease in a number of locations in response to the initial 2-week opening of the culverts in June-July 2002 (Figure 15). It is unlikely that this reflects a natural seasonal decline since others have shown that leaf N content varies little between June and August (Boar 1996). However, concentrations in June and July of 2003 were similar to those from samples collected prior to any introduction of seawater (2002) (Figure 16). One possible explanation is that the initial opening led to salinity shock following the abrupt change of conditions. In contrast, *Phragmites* emerging in 2003 had the entire spring and early summer period to acclimate to the "open" conditions. In addition, porewater nutrient levels were higher in 2003 than in 2002 (see the following section), which may have compensated to a certain extent for the effects of salinity and sulfide stress in *Phragmites*. For example, N is used to produce osmoregulatory amino acids such as proline in response to elevated salinities **(**Hartzendorf and Rolletschek 2001**)**. With prolonged exposure to full-strength seawater, however, it is expected that leaf total N content will be much reduced - either as a result of sulfide toxicity (Chambers et al 1998) or osmotic stress (Lissner and Shierup 1997), both of which reduce N assimilation, or a combination of both. Tissue sampling and N analyses will be continued in order to assess the time scales over which this reduction may occur.

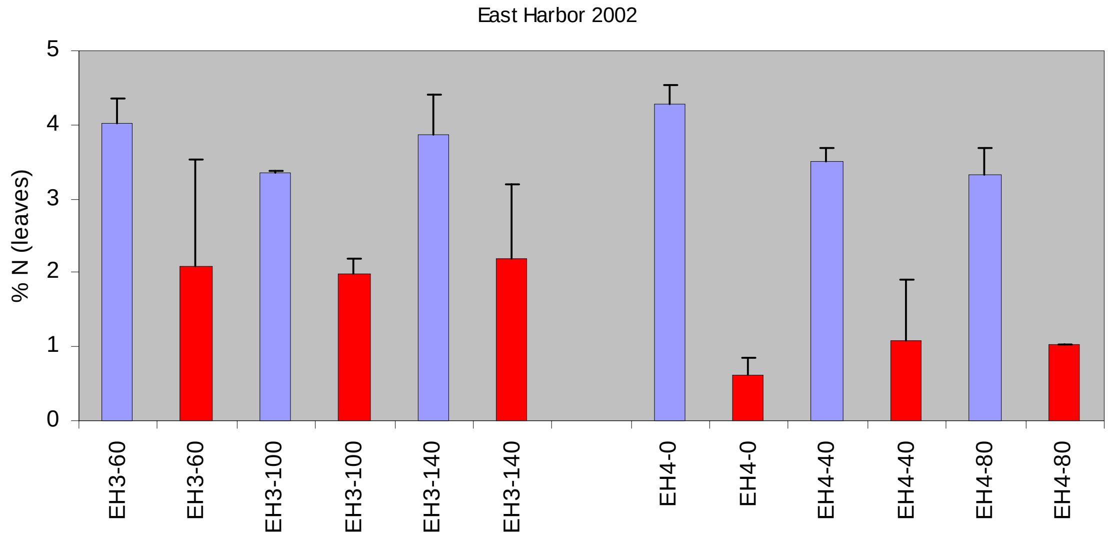


Figure 15. Leaf nitrogen content of *P. australis* before (June 18, 2002) and after (July 12, 2002) culvert opening.

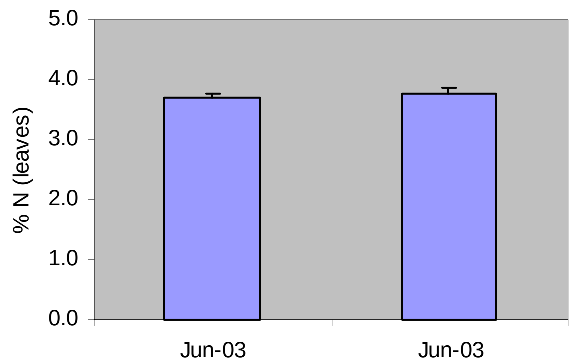


Figure 16. Leaf nitrogen content of *P. australis.*

Porewater quality - By and large, porewater salinities (at a depth of 10 cm below ground) showed very little increase along EH1 and EH2 compared to the previous year (only plots within ~20 m of the lake edge increased substantially). By contrast, salinities increased by ~20 ppt along transects EH3 and EH4 (Figure 17a). Porewater sulfides increased substantially along all transects, with the largest increases occurring along EH4 (Figure 17b). June concentrations of NH_4 were elevated along 3 of 4 transects in 2003 compared to the previous year (Figure 17c). Porewater PO_4 exhibited even larger increases along all transects (Figure 17d).

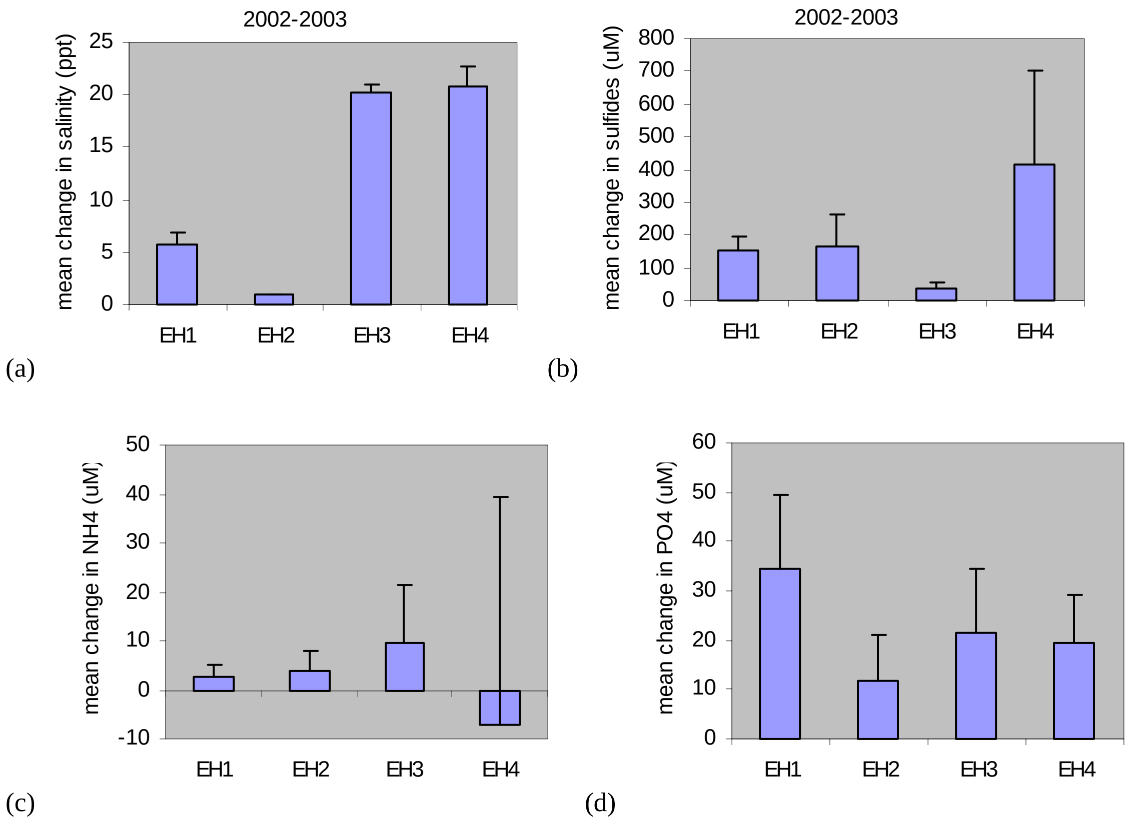


Figure 17. Mean change in porewater a) salinity, b) sulfides, c) NH_4, and d) PO_4 from June 2002 to June 2003 (plots pooled by transect).

Increased nutrient availability, particularly P, is likely a consequence of increased flooding since anaerobiosis would promote the reduction of Fe (III) minerals that bind PO_4. In addition, the increase in sulfate-rich seawater can increase the rate of nutrient mineralization in anoxic peat because SO_4 is superior energetically to CO_2 as an oxidant for organic decomposition and PO_4 release. Also, the system appears to be N limited based on N:P ratios of *Phragmites* leaf tissue (unpublished data) - thus it is expected than PO_4 would accumulate. On top of this, the death and decomposition of salt intolerant vegetation returns more nutrients to the substrate.

Finally, some interesting qualitative observations were made during the course of 2003 that indicate a rising degree of physiological stress in the *Phragmites* population of Moon Meadow. First, a number of plants exhibited leaf curl - a symptom of osmotic stress (Figure 18). Secondly, the leaves of many plants became infested with a species of green aphid (Figure 19), which was not observed on *Phragmites* elsewhere within East Harbor and within CACO itself.

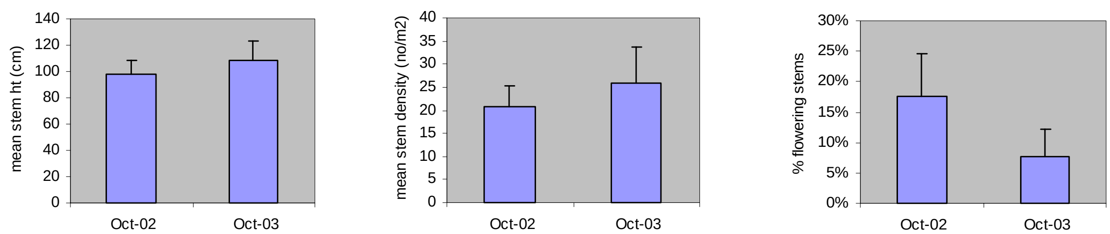
Figure 18. Osmotic stress as evidenced by leaf curling in *Phragmites* growing in East Harbor.

Figure 19. Aphids on a leaf blade of *Phragmites* from East Harbor.

Hatches Harbor – Restoring Side

<u>Vegetation</u>

As a whole (i.e., all plots pooled), *Phragmites* stem densities and heights increased slightly from 2002 to 2003 (Figure 20a, b) although in a statistical sense these changes were not significant. When broken down by plot, it becomes clear that the increases were largely due to changes in transect 2 plots distant from the main tidal creek (Figure 21, 22). Percent flowering exhibited the opposite trend with a reduction from 18% in 2002 to 8% in 2003 (Figure 20c). This difference, however, was not significant due to many plots that had non-flowering *Phragmites*, which contributed zero values to each group and increased the variance of the pooled means. On a plot by plot basis, however, the flowering response showed marked reductions along both transects (Figure 19).



(a) (b) (c)

Figure 20. *Phragmites* a) mean stem height, b) stem densities, and c) percent flowering stems for all plots in October 2002 and 2003 (error bars are standard errors of the means).

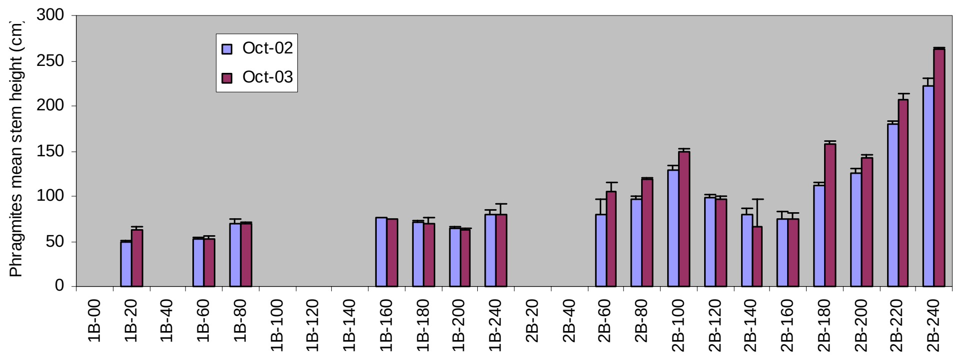


Figure 21. *Phragmites* mean stem heights by plot in October 2002 and 2003 (error bars are standard errors of the means).

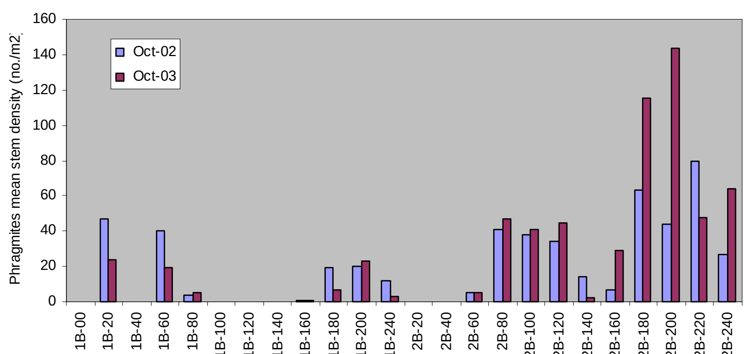


Figure 22. *Phragmites* stem densities by plot in October 2002 and 2003.

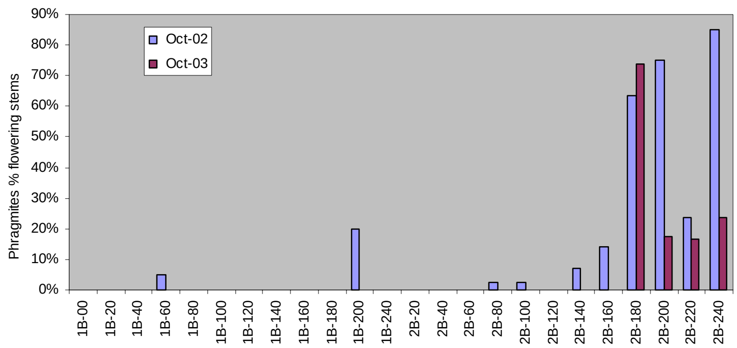
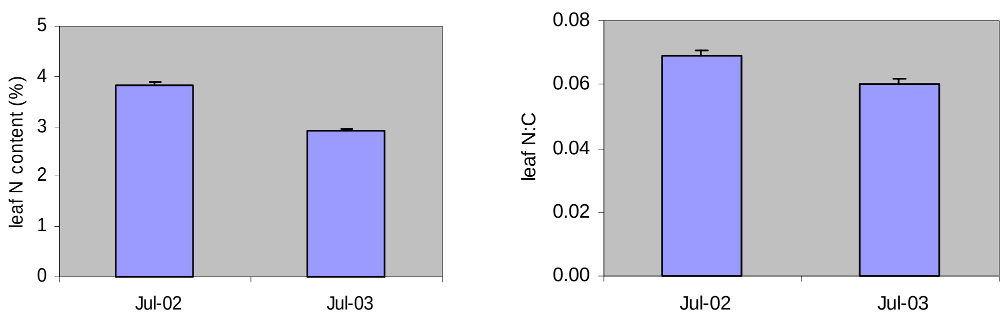


Figure 19. *Phragmites* percent flowering stems by plot in October 2002 and 2003.

Along transects 1 and 2, *Phragmites* leaf N concentrations ranged between 2.6 and 4.6% in July 2003 but showed no correlation with distance from the main tidal creek. N:C ratios similarly showed no spatial trends. However, leaf N and N:C in a small subset of plots (n=3) showed a decrease over the course of a year. In 2002, tissue samples were only collected from plots 1-20, 1-360, 1-540. When these were compared to 2003 samples from the same plots, a significant reduction is evident (Figure 23).



(a) (b)

Figure 23. *Phragmites* leaf tissue nitrogen (N) and nitrogen:carbon (N:C) in July 2002 and 2003 (values are means of plots 1-20, 1-360, 1-540; error bars are standard errors of the means).

Like in East Harbor, the small increase in *Phragmites* stem heights and densities may, to some extent, be due to differences in precipitation between 2002 and 2003. Figure 24 (below) shows how the progressive increase in porewater salinity along transect 2 was reversed in 2003 by the abundant rainfall.

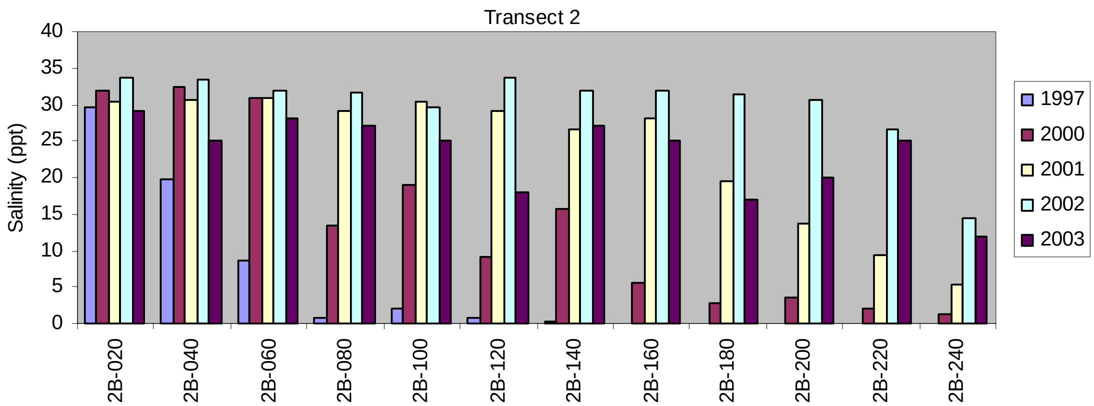


Figure 24. Porewater salinity by plot along transect 2 from 1997 – 2003.

Another possible explanation is the progressive loss of competition from salt-intolerant species that have either declined or died altogether. In Hatches Harbor there appears to be three zones of *Phragmites*. The first zone consists of short, sparse, non-flowering plants contiguous with the main tidal creek. Behind this is a second monospecific zone of dense, tall *Phragmites* growing in salinities that are now high enough to induce mortality in associate freshwater species. The third zone occurs in low salinity or freshwater areas distant from the tidal creek, often abutting upland habitat. Here, *Phragmites* is less dense and mixed in with a variety of freshwater wetland species. It appears that the zone of most vigorous *Phragmites* (second zone) growth is slowly moving back toward upland as seawater penetrates further into the marsh with each passing year.

The reduction in percent flowering stems at many plots is noteworthy and a stronger inhibition of flowering may emerge with increased seawater flow through the dike. Prolonged osmotic stress may deplete internal reserves to the point that plants forgo sexual reproduction. On a similar note, it appears that much of the *Phragmites* population (particularly plants closest to the main tidal creek) is senescing earlier in the year than populations growing under less stressful conditions - e.g., in lower salinity or freshwater environments (personal observation).

Lack of spatial gradients in leaf N content may be due to extremely low sulfide concentrations in this well-drained system. In fact, sulfides, which are known to inhibit N uptake, are frequently undetectable in this well-drained system. In addition, translocation of internal reserves through clonal integration may be occurring. Moreover, increased levels of porewater nutrients may be alleviating physiological stress in *Phragmites* and slowing its rate of decline. Nutrients can become more available through increased tidal flooding; also the death of salt-intolerant vegetation also contributes more nutrients to the system. This scenario has played out in manipulative experiments with marsh sediments (Portnoy and Giblin 1997) and in a nearby salt marsh restoration project (East Harbor, Truro) (unpublished porewater data).

Notwithstanding, we expect that continued flooding with full-strength seawater will act as a persistent drain on the internal reserves of *Phragmites*, thereby resulting in a weakened physiological state for the population in general. In addition, *Phragmites* will increasingly have to compete with greater numbers of native halophytes, which are spreading across the restricted side of the marsh. In response, the zones of *Phragmites* described above are likely to shift further back toward the upland fringes of the system, making way for a more expansive salt marsh community.

CONCLUSIONS

Although unrestricted salt marshes within CACO share many of the same plant taxa, relative species abundances are quite dissimilar, particularly with respect to macroalgae. In general, CACO's salt marsh habitats can be divided into two groups that sort out by coastline. The Cape Cod Bay-side marshes are generally richer with respect to species evenness and have more high marsh community types (e.g., *Spartina patens*, *Distichlis spicata*). In the lower tidal zone, *S. alterniflora* is very productive, attaining high levels of biomass over broad areas, and fiddler crabs are abundant in two of the three sites (Middle Meadow and West End). By contrast, the Atlantic-side marshes have fewer high marsh communities, were dominated by very short *S. alterniflora*, and contained no fiddler crabs.

Differences in vegetation composition and productivity are likely a function of soil drainage capacity, soil nutrient levels, elevations, and tidal range (Day et al. 1989). Although many different environmental factors contribute to plant nutrient status, the possibility exists that high *S. alterniflora* biomass and leaf N are manifestations of anthropogenic N inputs on a local (e.g., groundwater) or regional (e.g., atmospheric deposition) level. Currently, we have no explanation for the absence of fiddler crabs in Hatches Harbor, Nauset, and Pleasant Bay marshes. Notwithstanding, the relationship of marsh vegetation with various environmental variables will be explored using Canonical Correspondence Analysis and Multiple regression techniques. These analyses are dependent upon data that have yet to be generated through additional field work (e.g., elevation surveys) and laboratory analyses (e.g., sediment chemistry).

In East Harbor, vegetation and porewater exhibited substantial changes during the course of one full year of tidal restoration. In the southeastern part of the system (Moon Meadow area) plant species composition is being transformed as salt-intolerant taxa disappear. Porewater nutrients apparently have become more available as the system adjusts to the new hydrologic conditions (e.g. increasing ionic strength and cation exchange, increasing anaerobic decomposition). Although in the short term this may compensate somewhat for the effects of salinity stress in *Phragmites*, continued exposure to high salinities and sulfide concentrations should eventually result in a major decline in the population.

In Hatches Harbor, vegetation changes in the restricted side of the marsh are continuing. Although *Phragmites* made a slight recovery in places, probably due to copious rainfall in 2003, other indicators (e.g., flowering, tissue N) suggest an overall decline in vigor. Moreover, native halophytes are rapidly spreading throughout the (formerly) restricted marsh - a trend that should be statistically apparent following a complete vegetation survey that is scheduled for 2004.

Future Monitoring Activities and Recommendations

Preliminary synthesis of the 2003 data has provided a reasonable understanding of the structure and functioning of CACO's salt marsh habitat. To compliment this work, a small number of additional data needs have been identified. It is expected that this information will provide perspective and help answer specific questions that have emerged from the initial analyses.

1. Collect *S. alterniflora* height and tissue nitrogen data from other sites around Cape Cod that are presumed to have very different potentials for land-based anthropogenic nutrient enrichment (e.g., Town Cove, Monomoy, Nantucket, Muddy River).

2. Obtain *S. alterniflora* stem densities in unrestricted marsh sites. This information will also allow calculations of biomass and facilitate expressions of nitrogen in this species on an area basis (as per Bertness et al. 2002), both of which are critical for a regional perspective on CACO's salt marsh habitat.

3. Obtain values for percent flowering stems of *S. alterniflora* (rather than presence/absence of flowering stems).

4. Further investigate the apparent deterioration of certain parts of the Pleasant Bay marsh site. Anomalous signatures detected on aerial photographs will be reconnoitered to evaluate symptoms of deterioration should they be observed.

5. Develop an improved strategy for characterizing peat hydroperiod and aeration, including water-level sampling, redox monitoring and/or other methods.

6. Data analysis - Multivariate analysis (using BIOENV in Primer™ and regression analyses in Statistica™) will be conducted to determine most important factors regulating salt marsh structure and function. One component of the final analysis and discussion should be a characterization of CACO's unrestricted salt marsh habitat in a regional context. In other words, how do our marshes compare with those from around the Northeast Atlantic States? What are the differences and why do these differences exist?

Finally, to maintain a continuous, high-frequency level of data collection in the rapidly changing restoration projects, it is recommended that a complete vegetation survey of Hatches Harbor and East Harbor be conducted in 2004.

ACKNOWLEDGEMENTS

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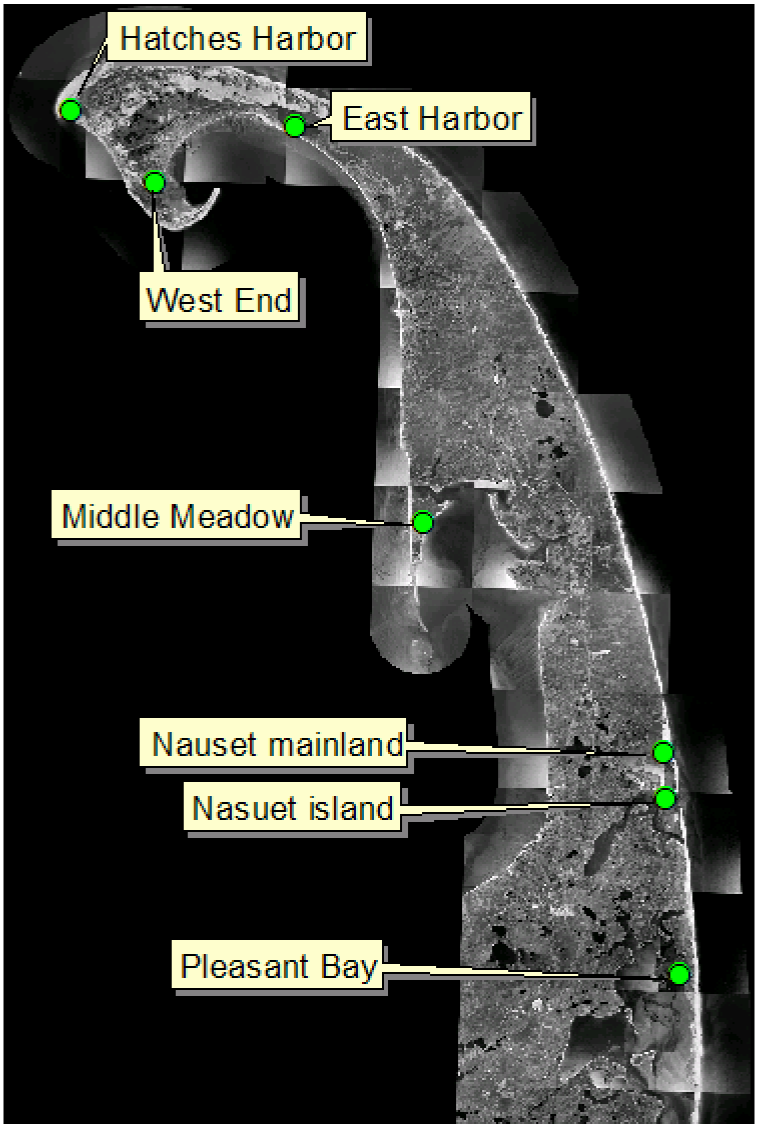
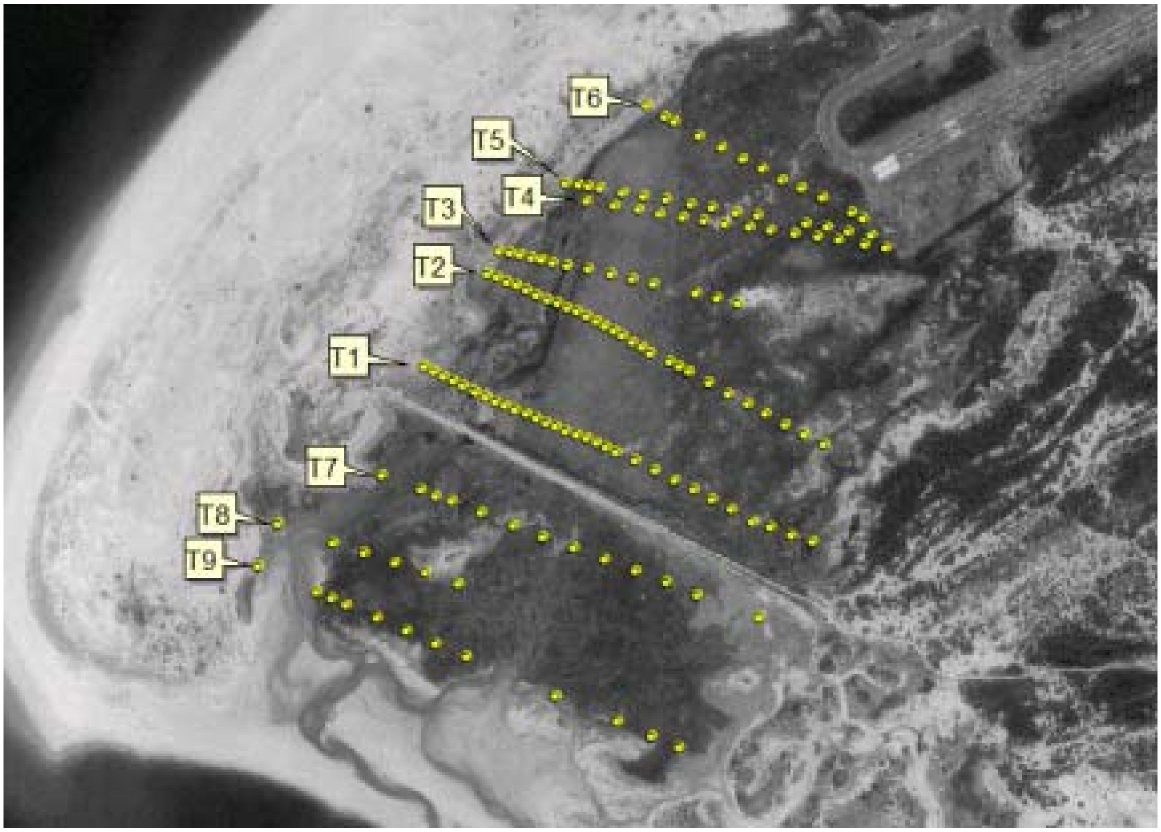
APPENDIX I. Maps of salt marsh monitoring locations

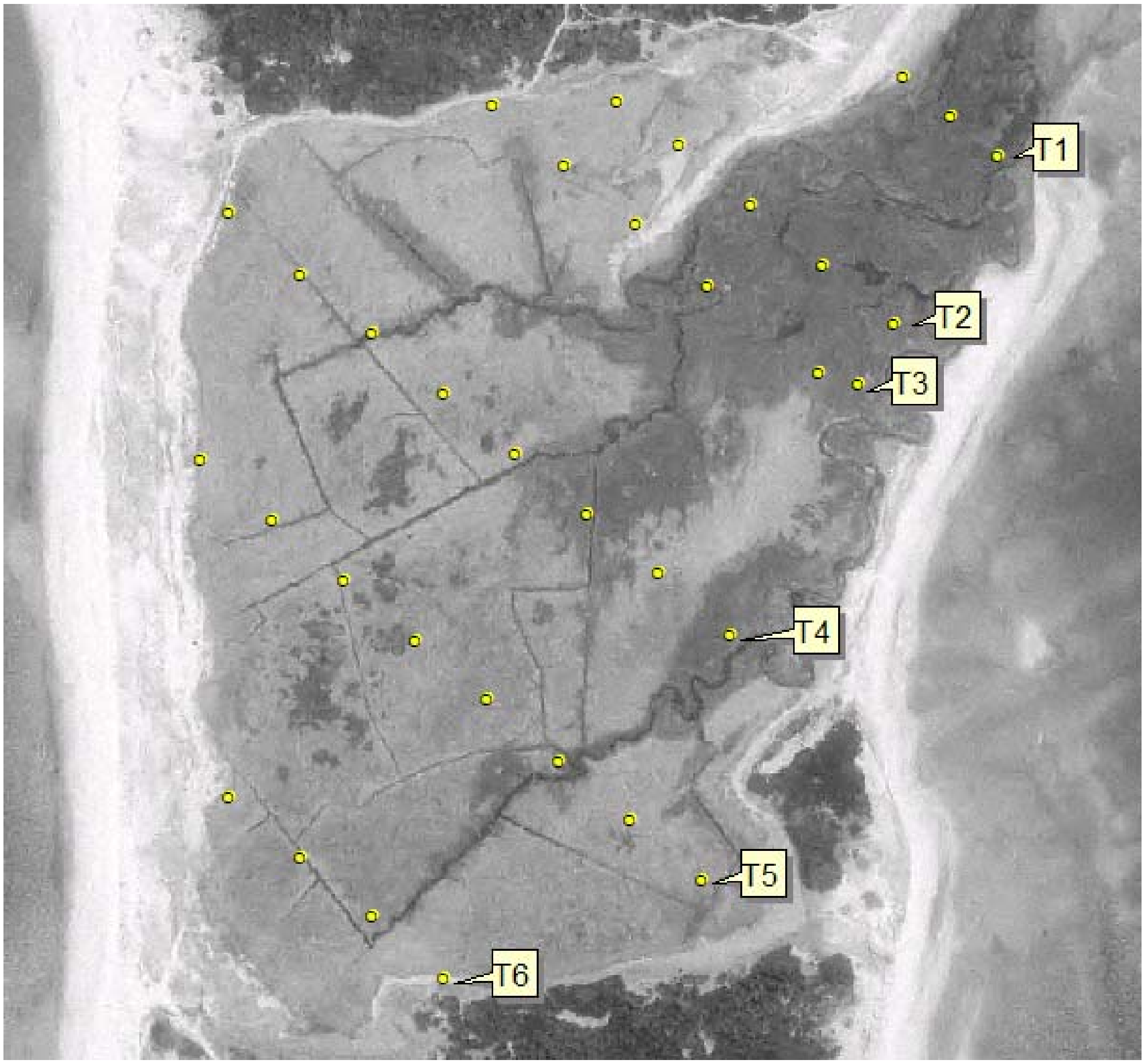


CACO salt marsh monitoring sites

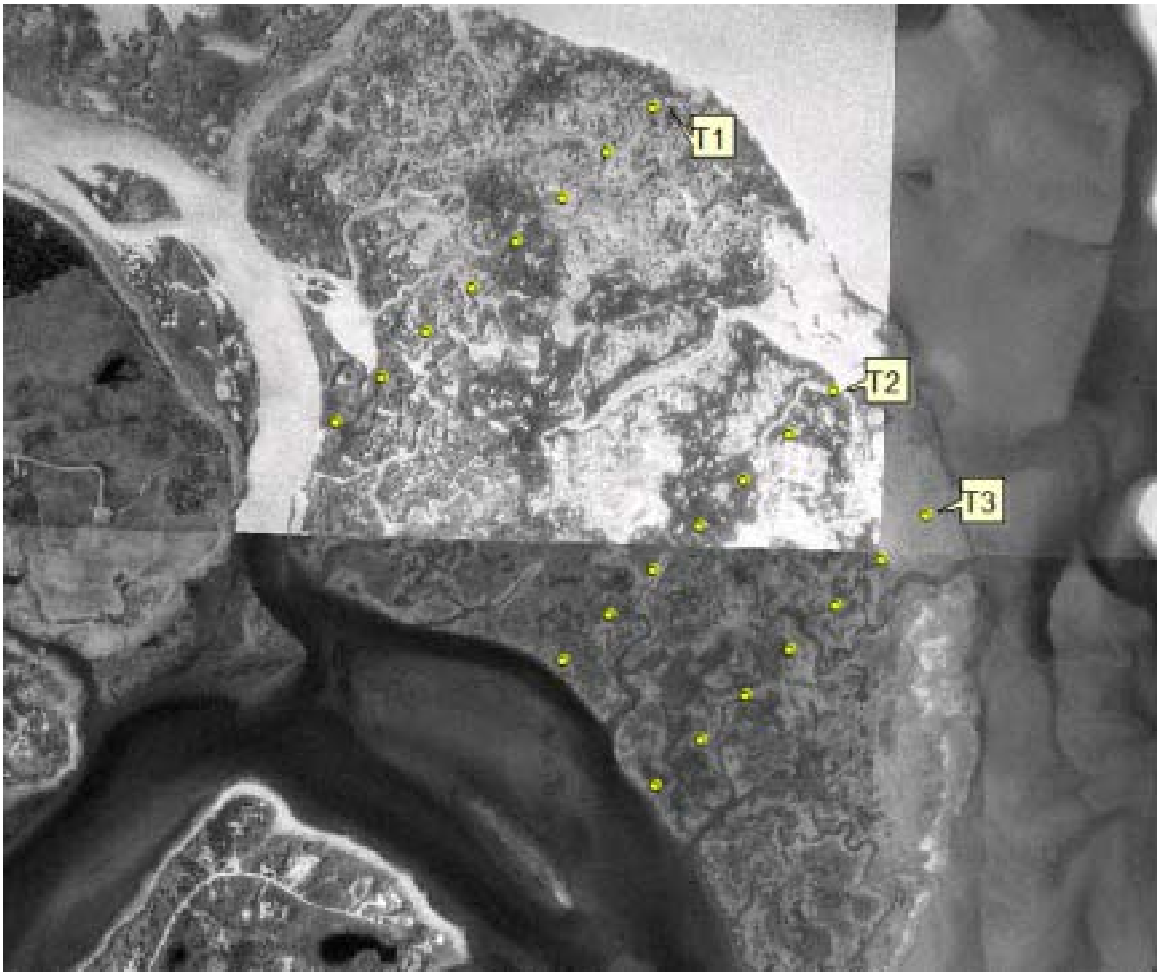


Hatches Harbor plot locations

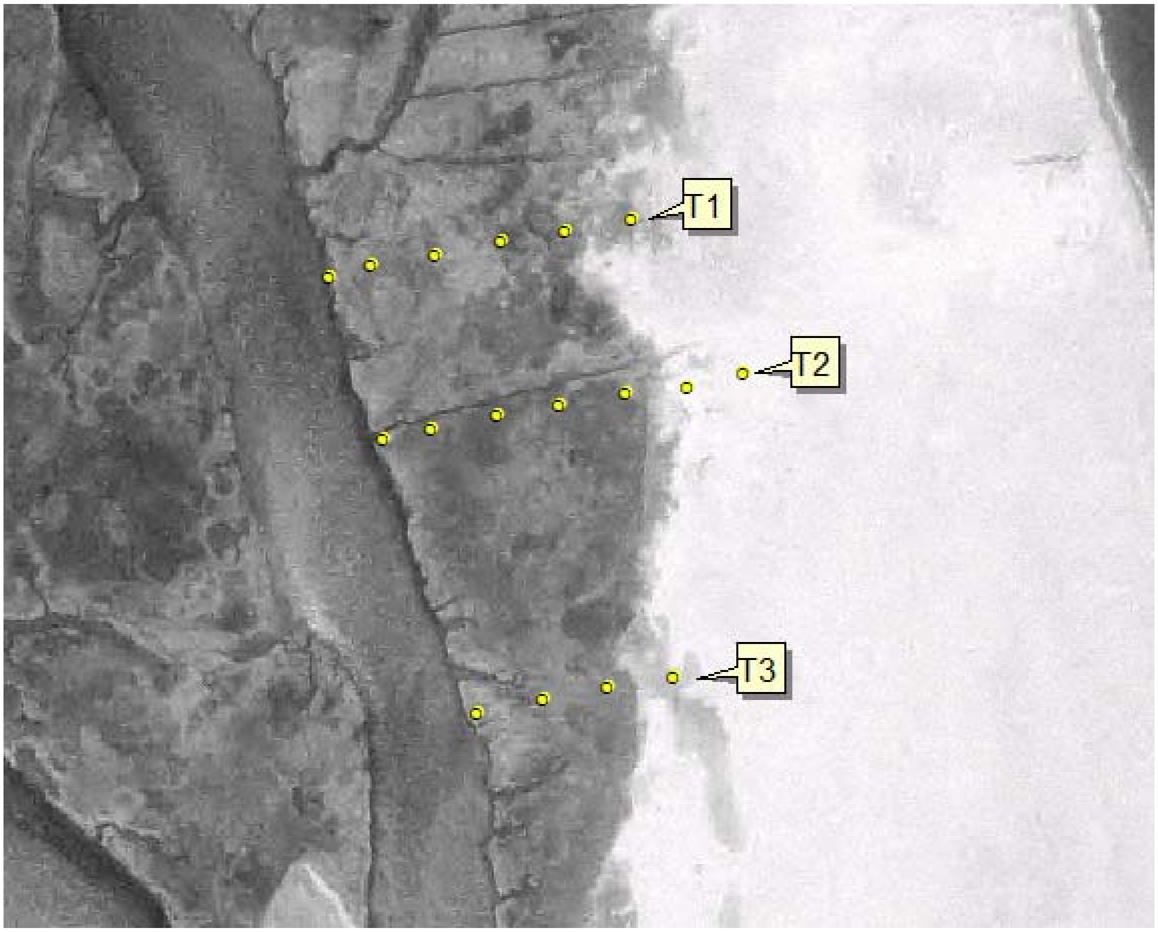
East Harbor plot locations



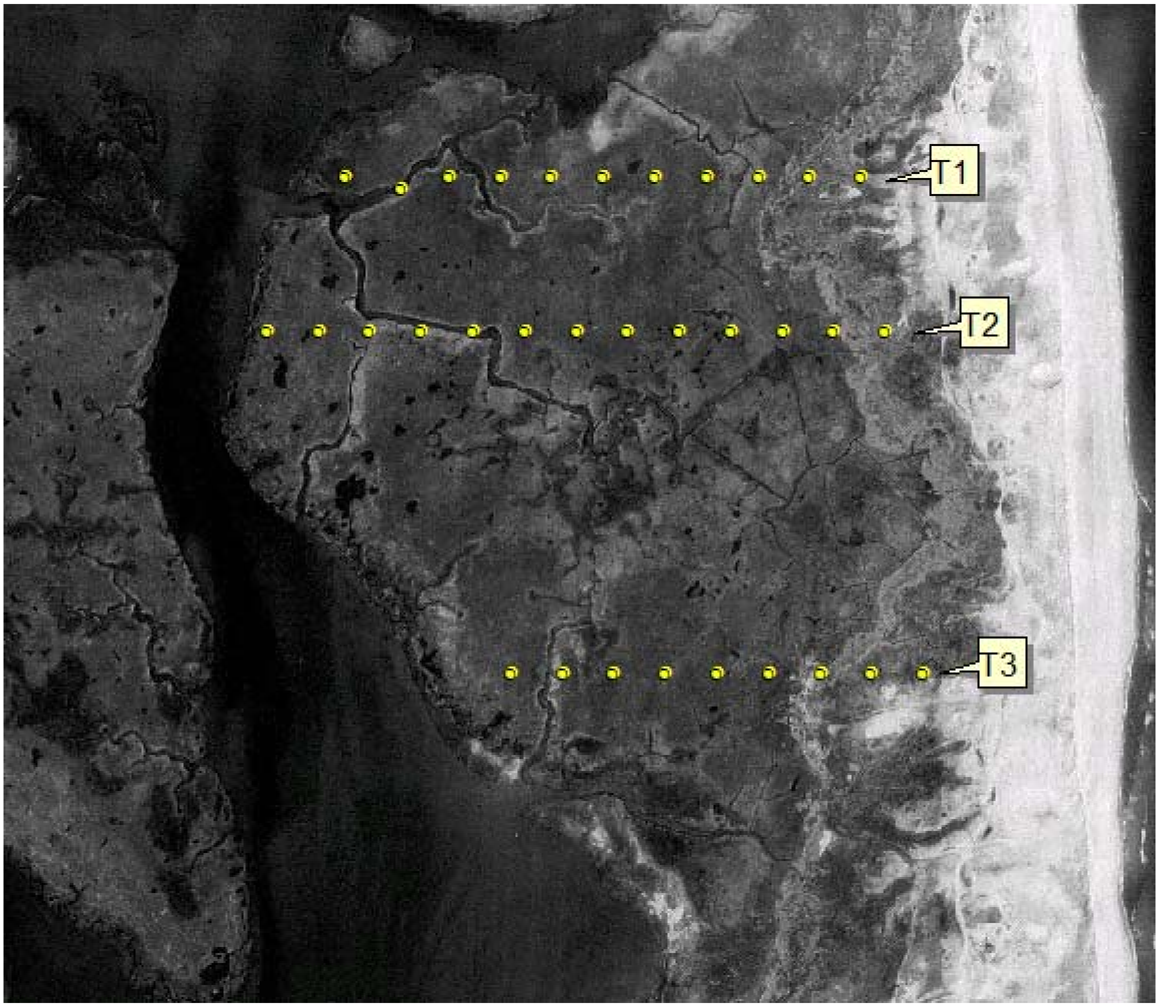
Middle Meadow plot locations



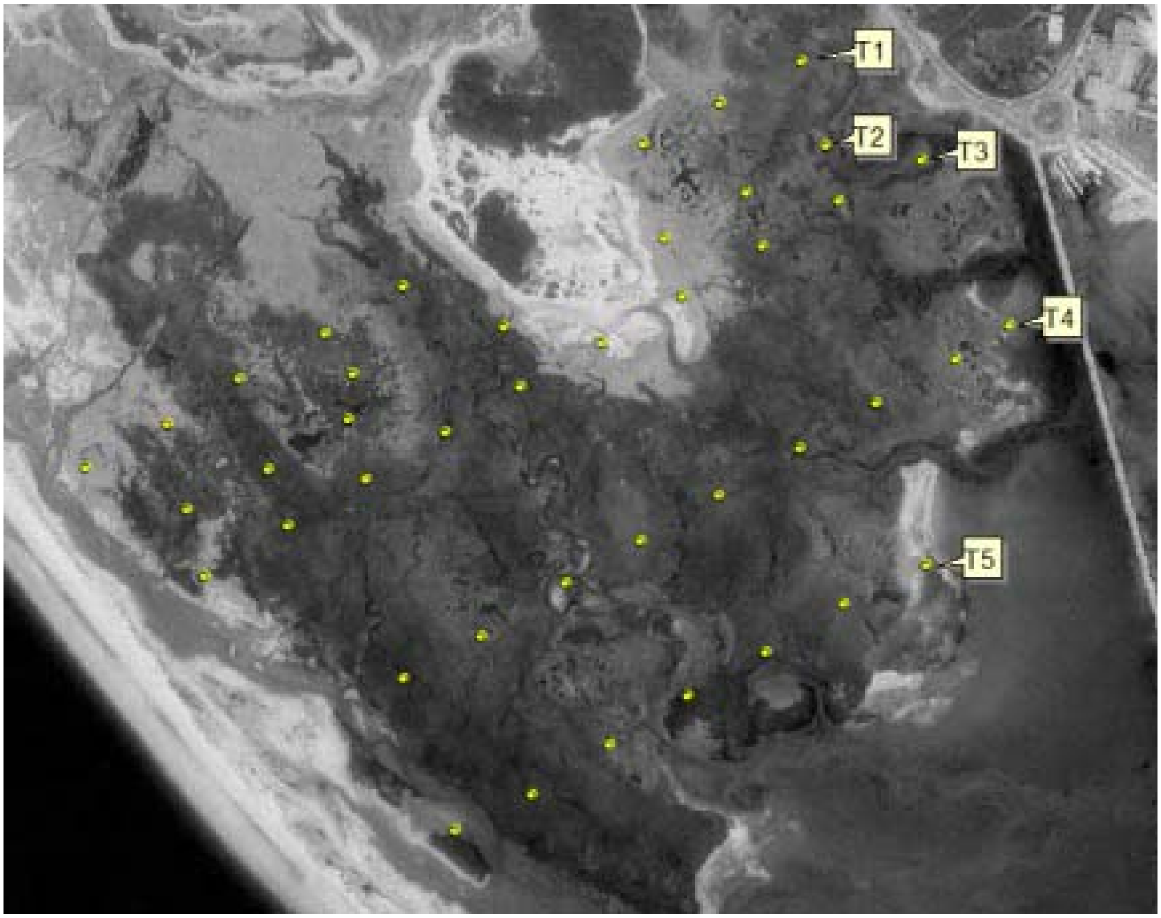
Nauset Island plot locations



Nauset mainland plot locations



Pleasant Bay plot locations

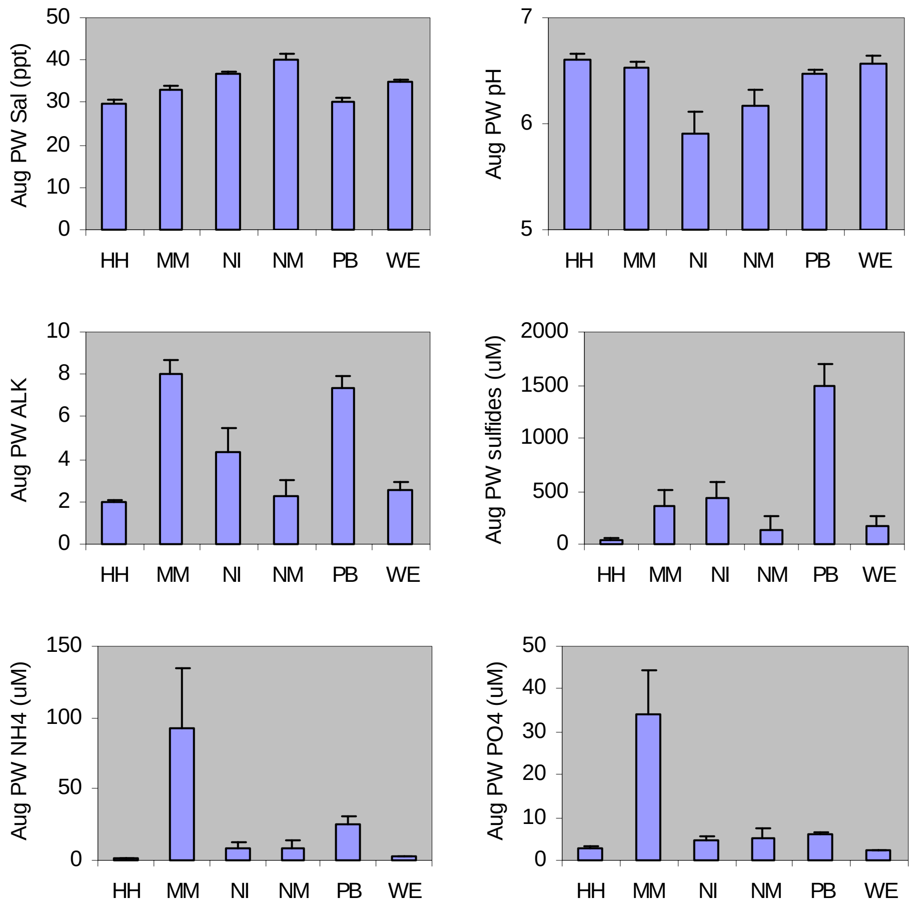


West End Marsh plot locations

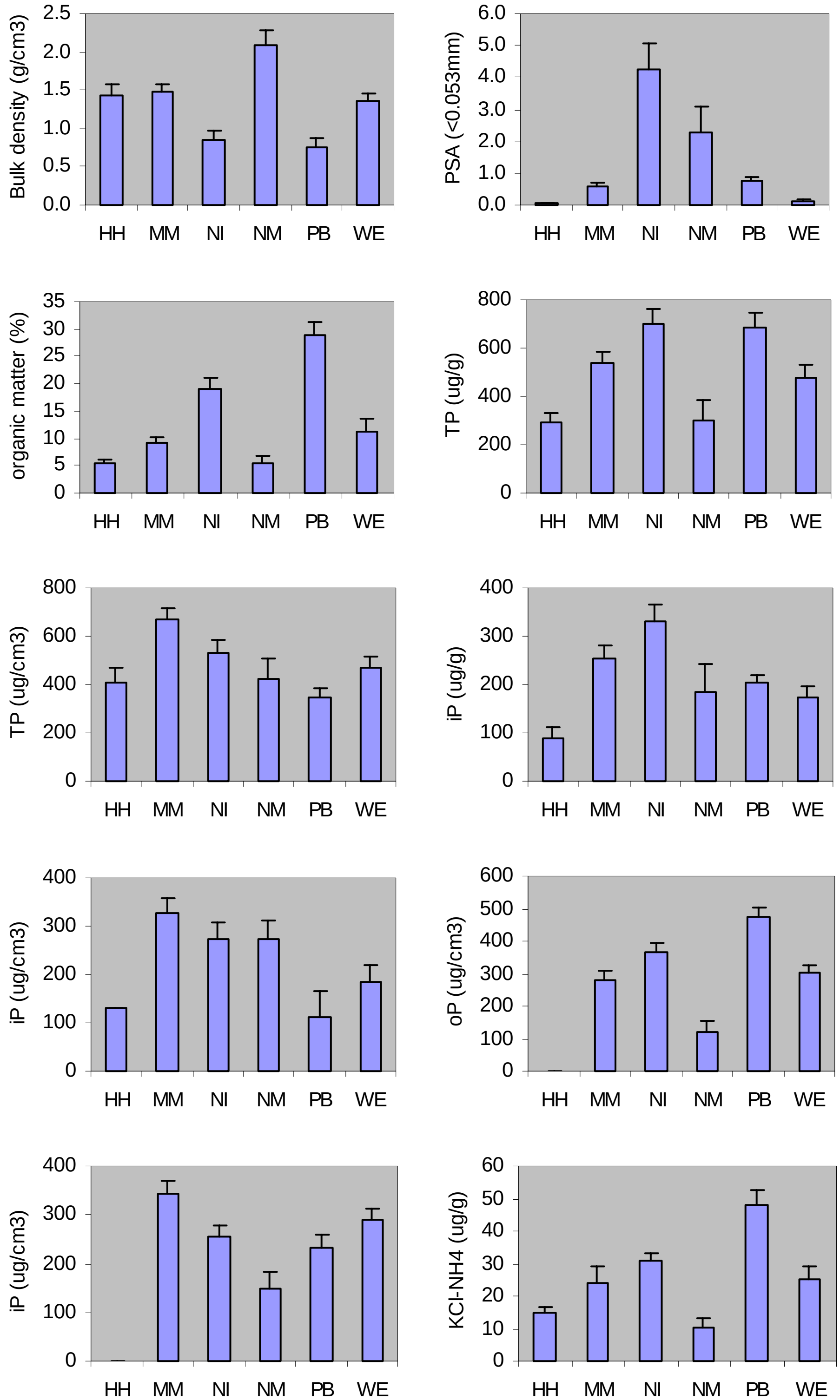
APPENDIX II.

Mean values for porewater and sediment variables from unrestricted marsh sites.

Porewater:



Sediments:


Bulk density (g/cm3)
0.0
0.5
1.0
1.5
2.0
2.5
PSA (<0.053mm)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
organic matter (%)
0
5
10
15
20
25
30
35
TP (ug/g)
0
200
400
600
800
TP (ug/cm3)
0
200
400
600
800
iP (ug/g)
0
100
200
300
400
iP (ug/cm3)
0
100
200
300
400
oP (ug/cm3)
0
100
200
300
400
500
600
iP (ug/cm3)
0
100
200
300
400
KCl-NH4 (ug/g)
0
10
20
30
40
50
60
HH
MM
NI
NM
PB
WE